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MICRO-g TRIAXIAL PIEZOELECTRIC SATELLITE
ACCELEROMETER SYSTEM DEVELOPMENT

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20 ABSTRACT (Continue on reverse side if necessary and identify by block number) A triaxial piezoelectric accelerometer was developed, fabricated, tested and calibrated for use in the NASA Get-Away-Special (GAS) to be flown on the space shuttle vehicle. It is to be used for the determination of the low-level vibration environment of the instrument pallet during orbital operation. for the possible measurement of orbital drag deceleration.			

FOREWORD

This document is the final report required under Contract No. F19628-79-C-0095 to develop a sensitive triaxial piezoelectric accelerometer for use in the NASA space shuttle Get Away-Special (GAS) program.

The author wishes to acknowledge the significant support and contribution of Mr. John I. Hudgins of the NASA Goddard Space Flight Center toward the development of the subject instrument.



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NOMENCLATURE

a	= Acceleration
C	= Capacitance, farads, microfarads
d	= Distance, inches
E	= Emf, volts
e	= Noise emf, volts
F	= Force, lbs, newtons
f	= Frequency, Hz
f_H	= Upper half-power frequency, Hz
f_L	= Lower half-power frequency, Hz
f_n	= Natural Frequency, Hz
G	= Piezoelectric modulus = 0.5
K	= Constant of proportionality
K_m	= Spring constant = 3.6×10^8 newtons/meter
k	= Relative dielectric constant
L	= Length, inches
M	= Mass, Kg
n	= Thermal noise coefficient = 1.26×10^{-10}
R	= Resistance, ohms
r	= Radius, inches
T	= Thickness, or tolerance, inches
V	= Voltage, volts
W	= Width, inches
Y	= Young's modulus = 1.42×10^9 newtons/meter
ϵ_0	= Permittivity (free space) = 8.85×10^{-12} farads/meter

ω = Frequency, angular velocity, radians/second

ω_n = Natural frequency, radians/second

1. INTRODUCTION

1.1 The GAS Program

The Get-Away-Special (GAS) program is a NASA-conceived system for the provision of cost-efficient experiment accommodation on their space shuttle vehicle. Essentially, it is comprised of a sealed cylindrical capsule of approximately the size of a standard 50-gallon drum which provides isolation for non-man-rated experiments. These capsules are mounted along the side bulkheads in the shuttle cargo bay.

The subject effort was to develop and fabricate a micro-g triaxial accelerometer to be placed in one of the GAS capsules to provide future GAS experimenters with orbital vibration data. Additionally, the instrument would gather air-drag data during early re-entry.

1.2 Specifications

The desired Get-Away-Special accelerometer operational specifications are listed below:

- a. Threshold sensitivity: $\leq 10^{-6}$ g
- b. Sensitivity Range: 10^{-6} to 10^{-2} g
- c. Frequency Range: 0.1 Hz to 300 Hz
- d. Output characteristics: Analog 0 to 5V or
-10 to +10 mv.
- e. Max. output of interest: 10^{-2} g
- f. Supply voltage: 28 ± 4 VDC

g. Operating temp. range: -20 to $+60^{\circ}\text{C}$

The non-operational specifications are:

- a. Temperature: -40 to $+80^{\circ}\text{C}$
- b. Acceleration: 3.5g
- c. Vibration: $0.1 \text{ g}^2/\text{Hz}$, 30 to 700 Hz
- d. Shock: 20 g , 11 msec

The GAS accelerometer will meet the following operational specifications.

- 1. Type: Damped piezoelectric cantilever bimorph
- 2. Sensitivity of transducer alone: 30 volts/g
- 3. Damping: 0.6 critical
- 4. Sensitivity with amplifier:
 - Output No. 1: $1 \times 10^2 \text{ v/g}$
 - Output No. 2: $1 \times 10^0 \text{ v/g}$
- 5. Sensitivity range: 1×10^{-6} to $1 \times 10^{-2} \text{ g}$
- 6. Signal output: Analog, 0 to 5v (data zero at 2.5v)
- 7. Transducer signal-to-noise ratio: 20 db ($10/1$) or greater
- 8. Frequency response: 0.1 to 300 Hz
- 9. Output impedance: 1500 ohms
- 10. Uncaging: Redundant dimple motor squibs
- 11. Power: $28 \pm 4 \text{ VDC}$, 150 ma
- 12. Signal-to-noise ratio at output: 8 db or greater
- 13. Temperature dependence: $0.24\%/^{\circ}\text{C}$

1.3 Configuration

The specifications were met by the use of three piezoelectric accelerometers of the cantilever bimorph type. The bimorph is comprised of a built-up beam or sandwich of lead-titanate lead-zirconate piezoelectric ceramic plates. This material exhibits excellent stability with respect to mechanical, thermal, and chemical environmental exposures. The beam or bimorph is configured to have a long, thin form factor having a rectangular section. One end is embedded into the frame of the instrument while the other is free. The free end is loaded with a heavy proof mass which, when under acceleration, generates a force which strains the beam in a simple bending mode. The bimorph produces a voltage proportional to strain and hence it produces a voltage proportional to acceleration.

Because of the heavy proof mass the accelerometer must be caged during launch to avoid fracture of the bimorph. Caging is accomplished by clamping the mass between the two jaws hinged to the case and held secure by a latch. To uncage the unit the latch is actuated by two redundant dimple motor squibs.

Three separate units are used which are mounted onto a base plate to form an orthogonal array. There are six analog outputs, two for each coordinate. Each unit has its own dc-dc converter to avoid cross interference. A timed 28 VDC, 1A, discrete is required

to fire the squibs after the spacecraft is stabilized in orbit. A temperature-sensing circuit is provided to monitor accelerometer temperature.

The voltage produced by the bimorph transducer is applied to an amplifier or signal conditioner to convert the voltage to that compatible with the TM or recorder system.

To cover the extended range of sensitivity required by the GAS system, the amplifier is designed with taps at two different gain levels; each level to cover two decades. This requires two TM channels per axis for data transmission. At low acceleration levels the low gain channel will show little or no information while the high gain will show useful information. At high levels the low gain channel will show useful information while the high gain channel is saturated. The amplifier outputs are sharply band-edge limited so that the voltage will not exceed the maximum TM input voltage.

A NASA-designed squib driver circuit is included to provide constant-current pulses to initiate the squibs for the uncaging operation. The electronics are mounted in a separate module which is bolted to the top surfaces of the three accelerometers.

2. PIEZOELECTRIC TRANSDUCER DESIGN

2.1 General

Figure 1 is a mechanical schematic of the sensor system. Three separate sensors are used in the accelerometer, arranged orthogonally, to measure the three orthogonal components of the acceleration vector. For frequencies below the natural frequency of the sensor the equivalent electrical circuit is shown at the bottom of Figure 1. The capacitance C is the internal capacitance of the transducer and the resistance R is the input resistance of the measuring circuit electronics. The voltage generator shown represents the internally generated voltage which at low frequencies is proportional to the acceleration experienced by the mass.

The mechanical system is essentially a base-excited spring attached to a mass. Such a system is spring-controlled above resonance and mass-controlled below resonance. That is, above resonance the applied force is opposed essentially by the spring force and the mass is effectively isolated, while below resonance the applied force is opposed essentially by the mass or inertial force. Hence, above resonance the sensor is a velocity-measuring device and below resonance it is an accelerometer.

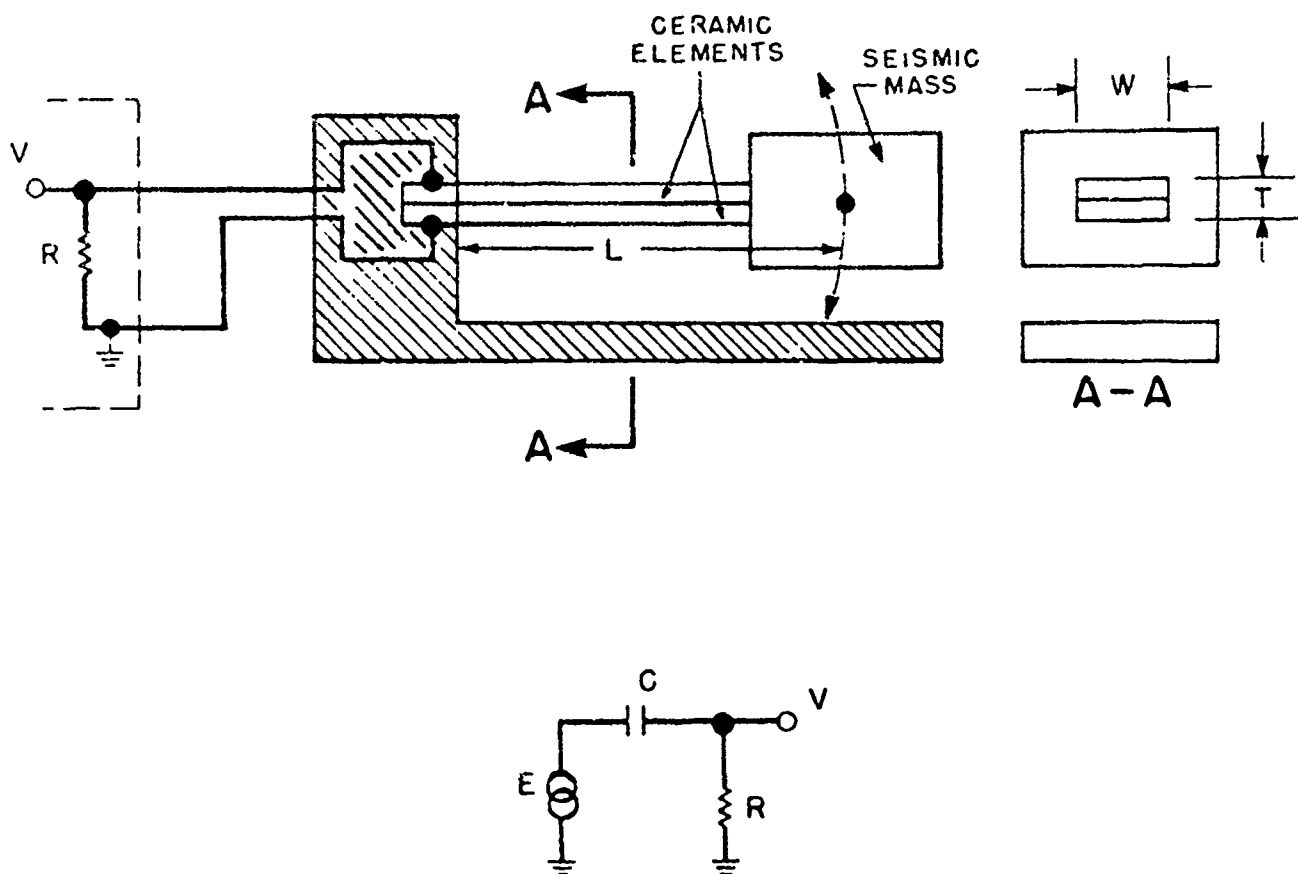


Figure 1

SENSOR ELECTROMECHANICAL SCHEMATIC
AND EQUIVALENT CIRCUIT

2.2 Transducer

The transducer element which has been selected for use in the accelerometer sensor design is a built-up beam or bimorph of synthetic piezoelectric multi-crystalline lead-zirconate lead-titanate (PZT). The advantages of PZT over other piezoelectric materials are:

1. High sensitivity
2. Good mechanical strength
3. High internal capacitance
4. Good chemical (incl. moisture) stability
5. Small size
6. Good thermal stability

Figure 2 is a side view of the bimorph showing the manner in which the beam is laminated. Each piezoelectric plate produces a voltage proportional to strain in the direction normal to its silvered surfaces. Thus, the plate produces a voltage when it is caused to become dimensionally thinner, and produces voltage opposite in polarity when it is caused to become thicker. The element is mounted as a cantilever beam, as shown in Figure 1, with the force due to acceleration applied to the free end. This causes the free end to deflect which in turn, because of Poisson cross coupling, causes one plate to become thinner while at the same time the other plate becomes thicker. In this manner the relatively low deflection force at the beam

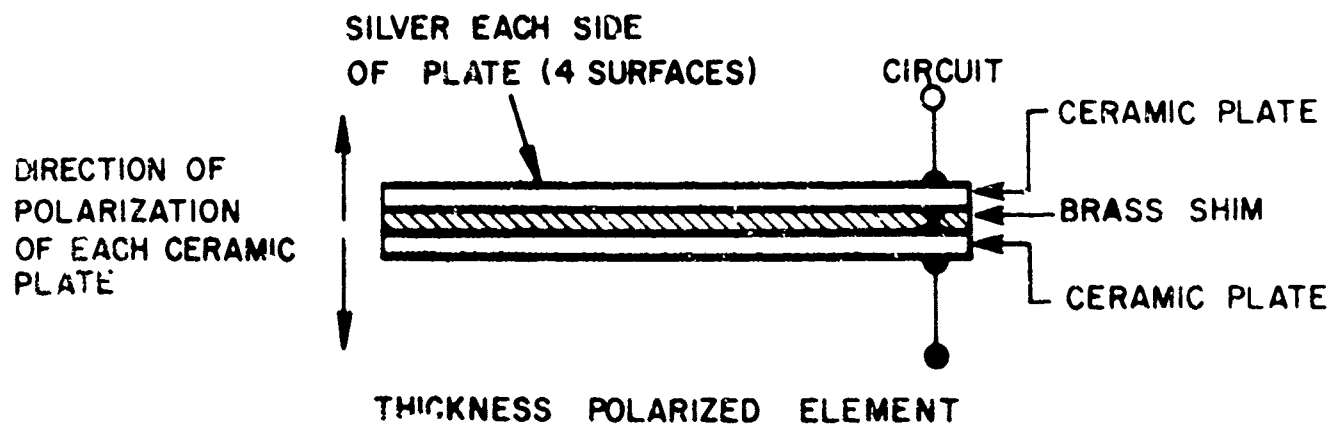


Figure 2
EDGE VIEW OF SIMORPH

end is amplified to become high tensile and compression forces at the plate surfaces.

2.3 Analysis

Figure 3 shows the response of the sensor. The solid curve is the normalized internally generated voltage of the transducer. The voltage appearing across the input resistance of the amplifier accurately follows this curve except at the low frequency end. There the response falls off to zero at zero frequency because of the internal capacitance of the transducer and is depicted by the left-hand dashed curve. The dashed curve at the right-hand side shows the modified response due to the filter in the amplifier. The roll-off is required to remove the resonant peak and to narrow the passband in the interest of noise reduction.

The low frequency response follows the well-known transfer function

$$\frac{V}{E} = \frac{1}{1 + \frac{1}{j\omega RC}} \quad (1)$$

which gives $V/E=0$ for $\omega=2\pi f=0$ and gives $\frac{V}{E}=\frac{\sqrt{2}}{2}$ for a frequency f_L where

$$\frac{1}{2\pi f_L RC} = 1 \quad (2)$$

This frequency f_L is known as the lower half-power frequency (because $\frac{\sqrt{2}}{2}$ squared equals $\frac{1}{2}$) and is used as a

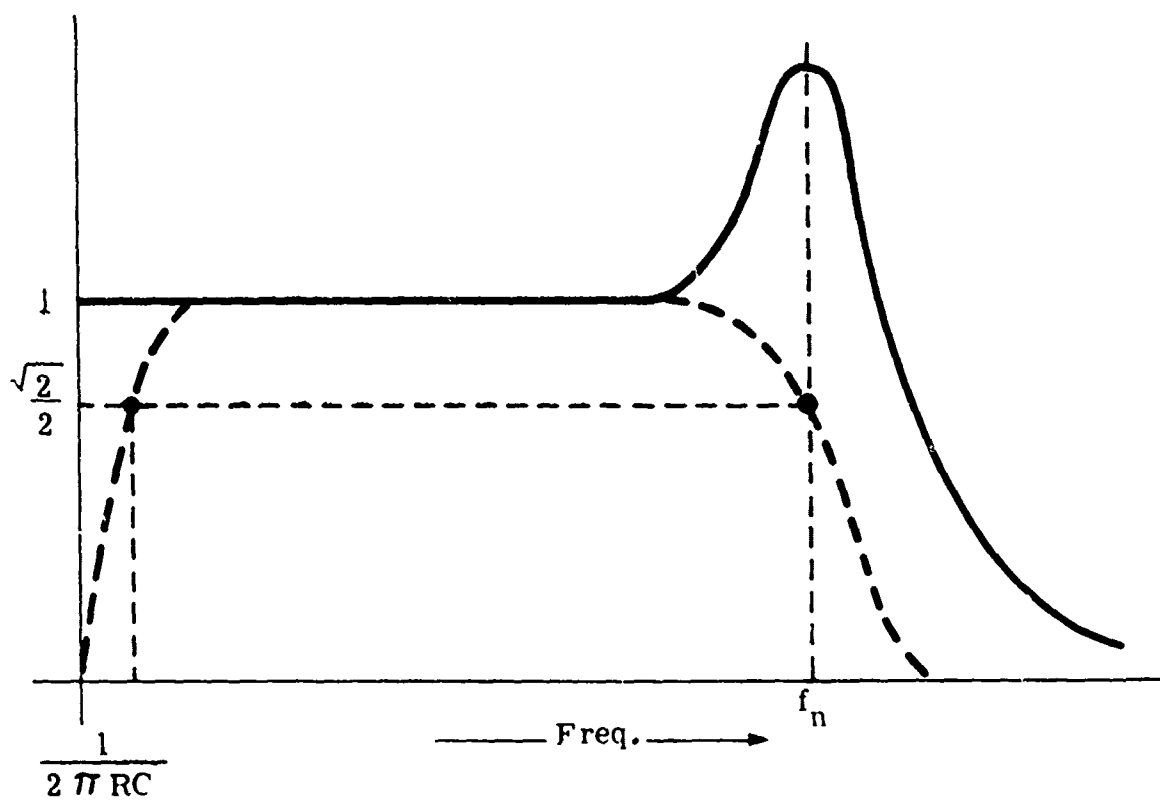


Figure 3
TRANSDUCER RESPONSE

measure of the lower limit of the sensor band-pass. Thus, the lowest frequency which will enable good coupling to the amplifier is given by Equation 2 or

$$f_L = \frac{1}{2\pi RC} \quad (3)$$

It is seen that the RC product must be high if the sensor is to respond to low frequencies. The capacitance C is controlled by the sizing of the transducer element. However, transducer sizing also controls the internally generated voltage for a given acceleration and determines the natural frequency of the sensor for a given mass load; hence, a set of design equations are required to enable one to make the necessary trade-offs. Similarly, while it appears that one should use the highest value of R as is practical to achieve the highest RC product, thermal noise voltage must be considered because this voltage increases with the value of R. The thermal noise generated by a resistor at ordinary ambient conditions is given by

$$e = n(R\Delta f)^{\frac{1}{2}} \quad (4)$$

where Δf is the bandwidth of the measuring system.

This equation can be made to represent both thermal and shot-effect noise by changing the constant n since shot-effect noise follows the same function to a close approximation.

A set of design equations may now be derived which enables one to optimize the signal-to-noise ratio of the system.

At frequencies below its natural frequency the transducer element (bimorph) produces a voltage proportional to the bending force given by

$$E = G \frac{L}{WT} F \quad (5)$$

where the symbols are defined and constant values given in the nomenclature.

For the sensor $F=Ma$ so that

$$E = G \frac{L}{WT} Ma \quad (6)$$

Combining Equations 4 and 6 gives the signal-to-noise ratio

$$\frac{E}{e} = \frac{G}{n} \frac{L Ma}{WT(R\Delta f)^{\frac{1}{2}}} \quad (7)$$

where $\Delta f = f_H - f_L$ is the difference between the upper and lower half-power frequencies. Combining Equations 3 and 7 to eliminate R yields

$$\frac{E}{e} = \frac{GL Ma}{nWT} \left(\frac{2\pi f_L C}{f_H - f_L} \right)^{\frac{1}{2}} \quad (8)$$

The capacitance of a bimorph is given by

$$C = k\epsilon_0 \frac{LW}{T} \quad (9)$$

Introducing this into Equation 8 gives

$$\frac{E}{e} = \frac{G}{n} \left(\frac{L^3 M}{WT^3} \right)^{\frac{1}{2}} \left(\frac{2\pi k\epsilon_0 Mf_L}{f_H - f_L} \right)^{\frac{1}{2}} \quad (a) \quad (10)$$

The natural frequency of the sensor is given by

$$\omega_n = 2\pi f_n = \left(\frac{K_m}{M} \right)^{\frac{1}{2}} \quad (11)$$

where K_m , the bimorph stiffness, is given by

$$K_m = \frac{Y}{4} \frac{WT^3}{L^3} \quad (12)$$

which, when combined with Equation 11, gives the natural frequency in terms of bimorph parameters and mass load as

$$2\pi f_n = \left(\frac{Y WT^3}{4 L^3 M} \right)^{\frac{1}{2}} \quad (13)$$

the reciprocal of which is exactly proportional to the first bracketed factor of Equation 10. Thus, the signal-to-noise ratio becomes

$$\frac{E}{e} = \frac{G}{n} \left(\frac{k\epsilon_c Y}{8\pi} \right)^{\frac{1}{2}} \left(\frac{Mf_L}{f_H - f_L} \right)^{\frac{1}{2}} \frac{a}{f_n} \quad (14)$$

or

$$\frac{E}{e} = K_1 \left(\frac{Mf_L}{f_H - f_L} \right)^{\frac{1}{2}} \frac{a}{f_n} \quad (15)$$

Evaluating Equation 15 with the required bandwidth, natural frequency (which must lie above the passband), signal-to-noise ratio (ideally 10 or above), and threshold acceleration enables one to obtain the Mf_L product as a constant K_2 which, when combined with Equation 3, enables trades to be made between M , R , and C .

$$Mf_L = K_2 = \frac{M}{2\pi RC} \quad (16)$$

At this point a selection for R is made based upon amplifier requirements such as gate leakage current (stability), insulation limitations and other electrical considerations. This gives a trade-off equation for M and C

$$K_3 = \frac{M}{C} \quad (17)$$

Combining Equation 17 with Equations 9 and 13 enables trades to be made in the bimorph parameters W , L , and T .

Bimorph parameters are limited, of course, by packaging constraints and availability of particular sizes from the vendor which requires additional iterations in making trades and arriving at a final design.

The final design has the following parameters:

$$W = 0.827 \text{ inches}$$

$$L = 1.75 \text{ inches}$$

$$T = 0.346 \text{ inches}$$

$$M = 288 \text{ grams}$$

$$R = 3.6 \times 10^8 \text{ ohms}$$

$$C = 4.5 \times 10^{-9} \text{ farads}$$

To allow a design having a lower natural frequency and hence a greater sensitivity (larger proof mass), the resonant rise at the upper end of the frequency range is damped by the use of silicone oil. The transducer case is sealed allowing the transducer to be totally immersed in the fluid.

3. CAGING

3.1 General

The high sensitivity of the accelerometer is achieved by optimization of the piezoelectric transducer element design and by the use of as large a proof mass as the element design and the bandwidth requirement will permit. In the GAS accelerometer design, this mass is 288 grams or 0.63 lbs. The space shuttle during the launch phase produces a maximum shock acceleration of 20 g's producing an impulsive force of over 12 lbs at the proof mass which in turn applies bending, tension, and compression forces of the same magnitude to the transducer element. These elements, being of a brittle ceramic, would fracture if provision was not made for the clamping of the proof masses during the launch phase of the mission.

This clamping or caging is provided by a mechanism that is engaged prior to launch and is then disengaged after orbit is achieved by the use of pyrotechnique devices.

3.2 Design

Because the applied accelerations due to the launch environment are largely linear, as opposed to angular, the caging mechanism is a balanced rotational device. Thus a linear acceleration will not produce net forces

on the mechanism causing premature uncaging.

The design is comprised of two wheels each having two pairs of closely spaced teeth at diametrically opposite positions on their rims. These wheels are centered close to each side of the proof mass with their common axis normal to the accelerometer sensing axis. Crossing over the top and bottom of the proof mass are plates having matching teeth on their extremities which engage the corresponding teeth on the wheels. These plates in turn have cone-point set screws which engage dimple recesses on the top and bottom surfaces of the mass to confine the mass in the two coordinate directions normal to the sensing axis.

At quadrature to the tooth positions on the wheel is a transverse pressure bar connecting the wheels into one assembly. Opposite the pressure bar are located trim masses attached to the wheel rims to provide balance. Positioned against the pressure bar are two side-by-side pusher pins whose thrust axes are tangential to the wheel rims. Against the pusher pins are placed redundant dimple motor squibs (Hercules 25 J5). Initiation of the squibs causes translation of the pressure bar which in turn causes rotation of the wheels. The angle of rotation is sufficient to disengage the wheel teeth from the corresponding teeth of the cage plates, allowing the plates to move away from the proof mass. The plates are confined to translation

along the sensing axis by stub shafts located at their centers and which protrude into bushing holes in the instrument case. Translation of the plates upon disengagement is generated by the force exerted by leaf springs which press against their inward sides.

Particular attention had to be paid to the vibrational modes of the caging mechanism when uncaged to avoid resonances between cage mechanism component natural frequencies and measured (input) acceleration frequencies.

Because of the low amplitude of the measured accelerations and because the instrument is damped with silicone oil, the effect of these parasitic frequencies is controlled largely by placing component parts against the case and against each other with optimized contacting surfaces so that the thin oil film acts as an adhesive to bind the parts against the stiffer structure thus preventing their independent flexure. The caging mechanism is shown schematically in Figure 4.

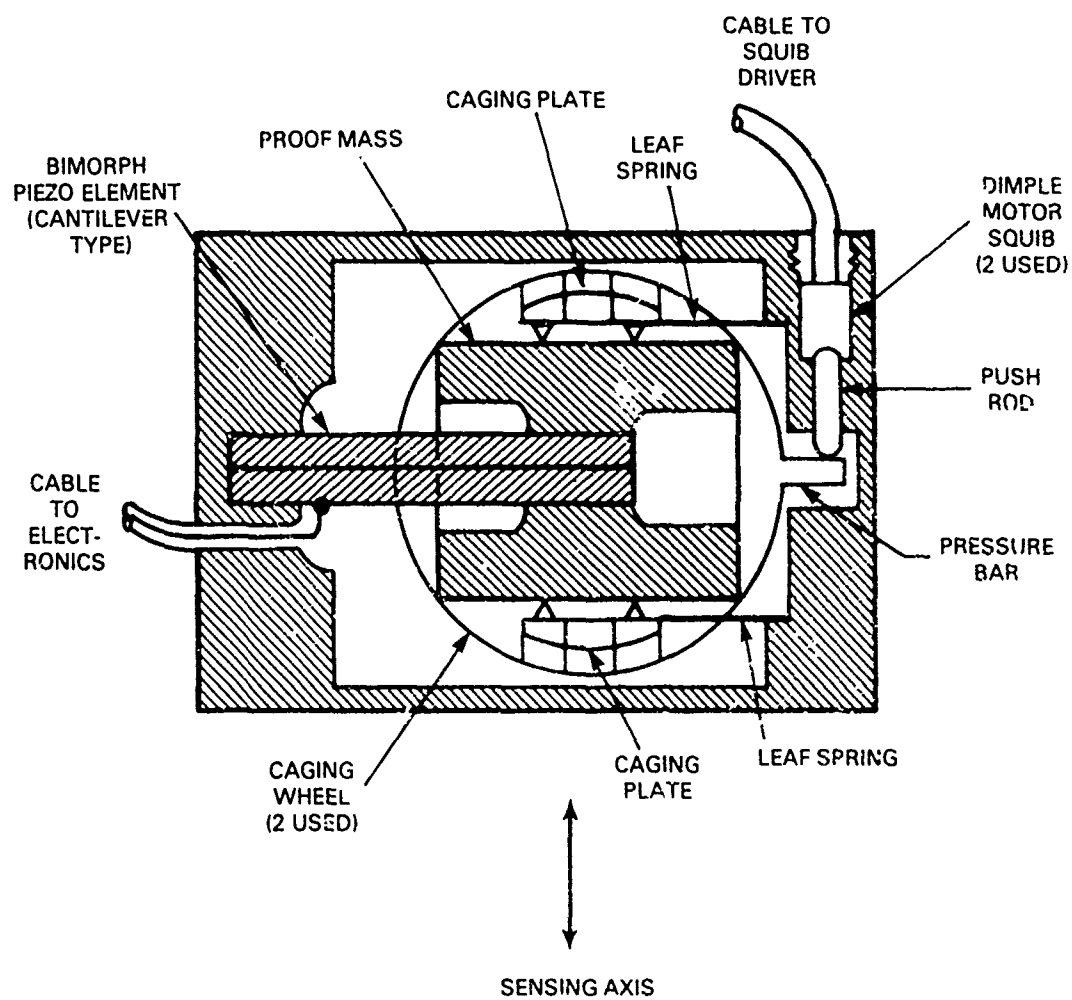


Figure 4

SECTION VIEW OF ACCELEROMETER MODULE (3 USED)

4. MECHANICAL DESIGN

4.1 General

The GAS accelerometer is comprised of three, single-axis accelerometers placed orthogonally to form a composite triaxial accelerometer. Each of the three units is independently sealed and cabled into an electronics package placed over the units to form an approximate cube of the aggregate. The electronics package contains the accelerometer amplifier, the squib driver and temperature monitor circuits. The configuration is shown in the photograph, Figure 5, and in the outline drawing Figure 6.

4.2 Structure

All cases are of 7075 aluminum alloy of sufficient thickness to avoid modes of vibration at frequencies within the measuring range. All caging mechanism components are of stainless steel and are shaped and fitted to avoid parasitic resonances as discussed above in Section 3. Sealing is accomplished by the use of neoprene O-rings and by silicone rubber gaskets.

The amplifiers are modular and are potted in E-C 286 epoxy. The amplifiers are fabricated of etched glass boards and the squib driver and temperature monitor circuits are mounted on a fiberglass board using point-to-point wiring which is potted in Dow 170 silicon rubber.

The three accelerometers are bolted orthogonally onto a base plate carrying the instrument mounting

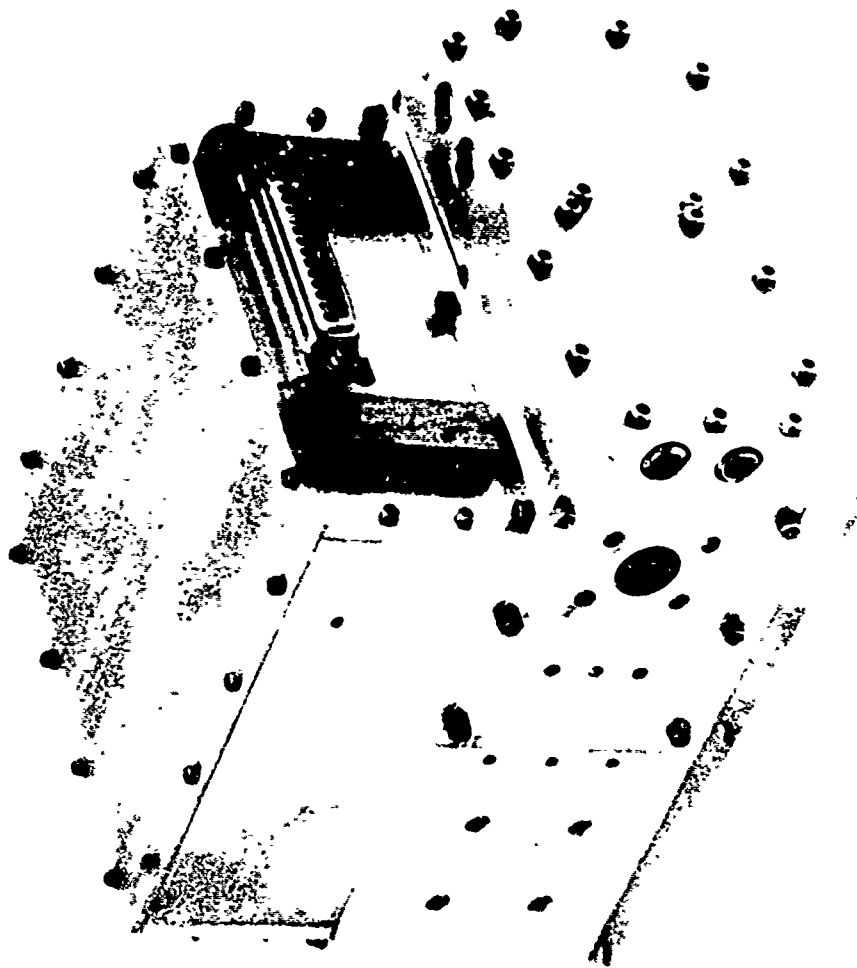
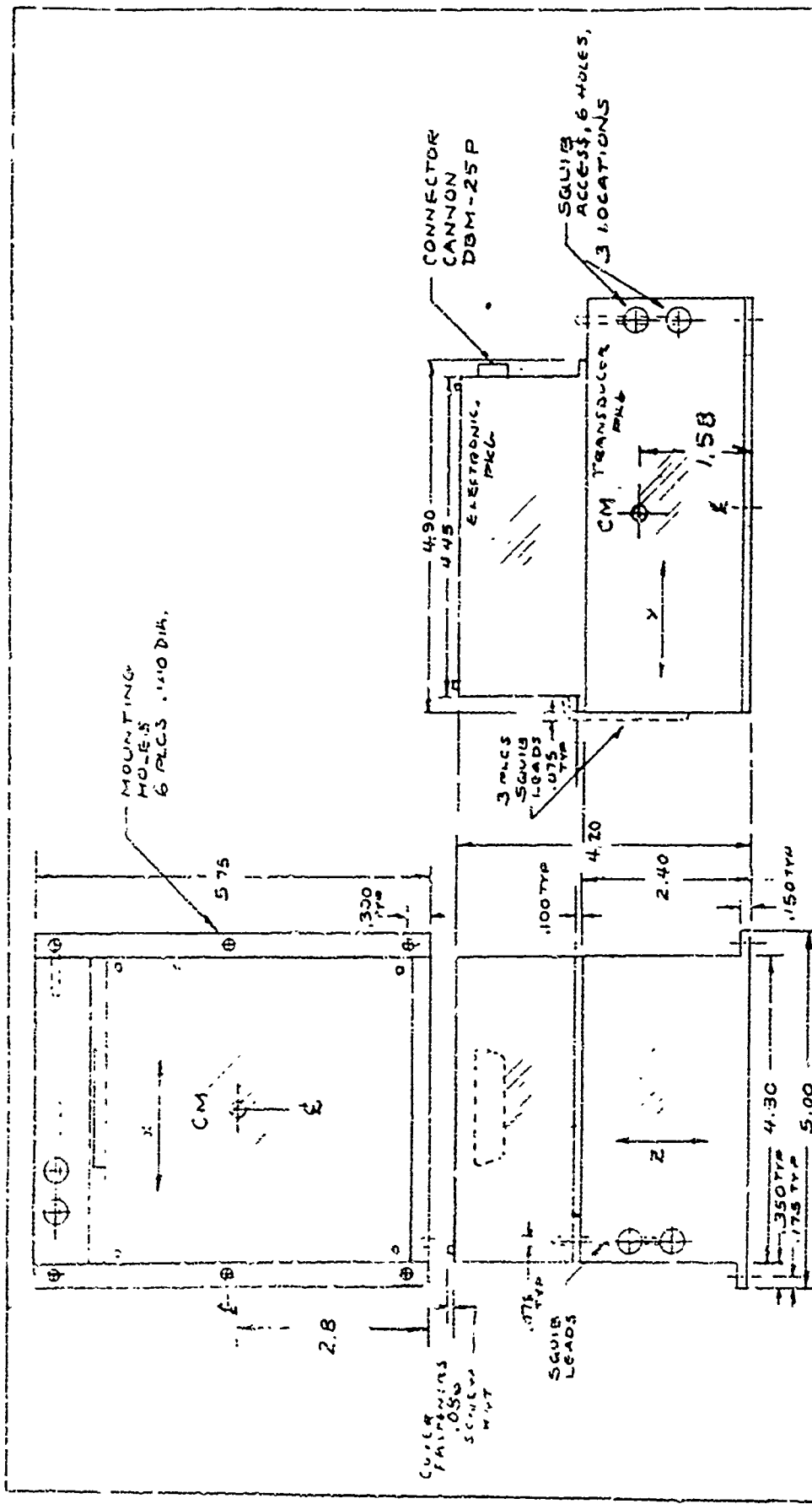


Figure 5
GAS MICRO-g TRIAXIAL ACCELEROMETER



NOTES:
 1. TOTAL WEIGHT-10 LBS.
 2. ALL DIMENSIONS IN INCHES.

FIGURE 6

REV	DATE	DESCRIPTION	APPROVED	DATE	DATE	SCALE	SCALE
D	ADDED CM	7/71	DESIGNED	7/71	DATE	7/71	100/21-D
C	REV W/	11/71	DESIGNED	11/71	DATE	11/71	
B	ADDED CM	1/72	DESIGNED	1/72	DATE	1/72	
A	ADDED CM	1/72	DESIGNED	1/72	DATE	1/72	
PERMIT SCALE FOR CONSTRUCTION				ACCELEROMETER COMPENSATION			
TOLERANCES UNLESS OTHERWISE SPECIFIED				CAMERON MASS 0110			
FRACTIONS UNLESS OTHERWISE SPECIFIED				CONCENTRICITY 0.010			
OVER 10 TO 1.00				CONCENTRICITY 0.010			
OVER 1.00 TO 1.00				CONCENTRICITY 0.010			
OVER 1.00 TO 1.00				CONCENTRICITY 0.010			

holes. The electronics package is a separate module which is bolted to the top surface formed by the three coordinate accelerometers. The accelerometer outputs are cabled to the amplifier inputs through holes provided in the underside of this module. The squib cabling is provided externally through Winchester connectors attached to the electronics module and to the extremities of the squib leads.

5. AMPLIFIER DESIGN

5.1 General

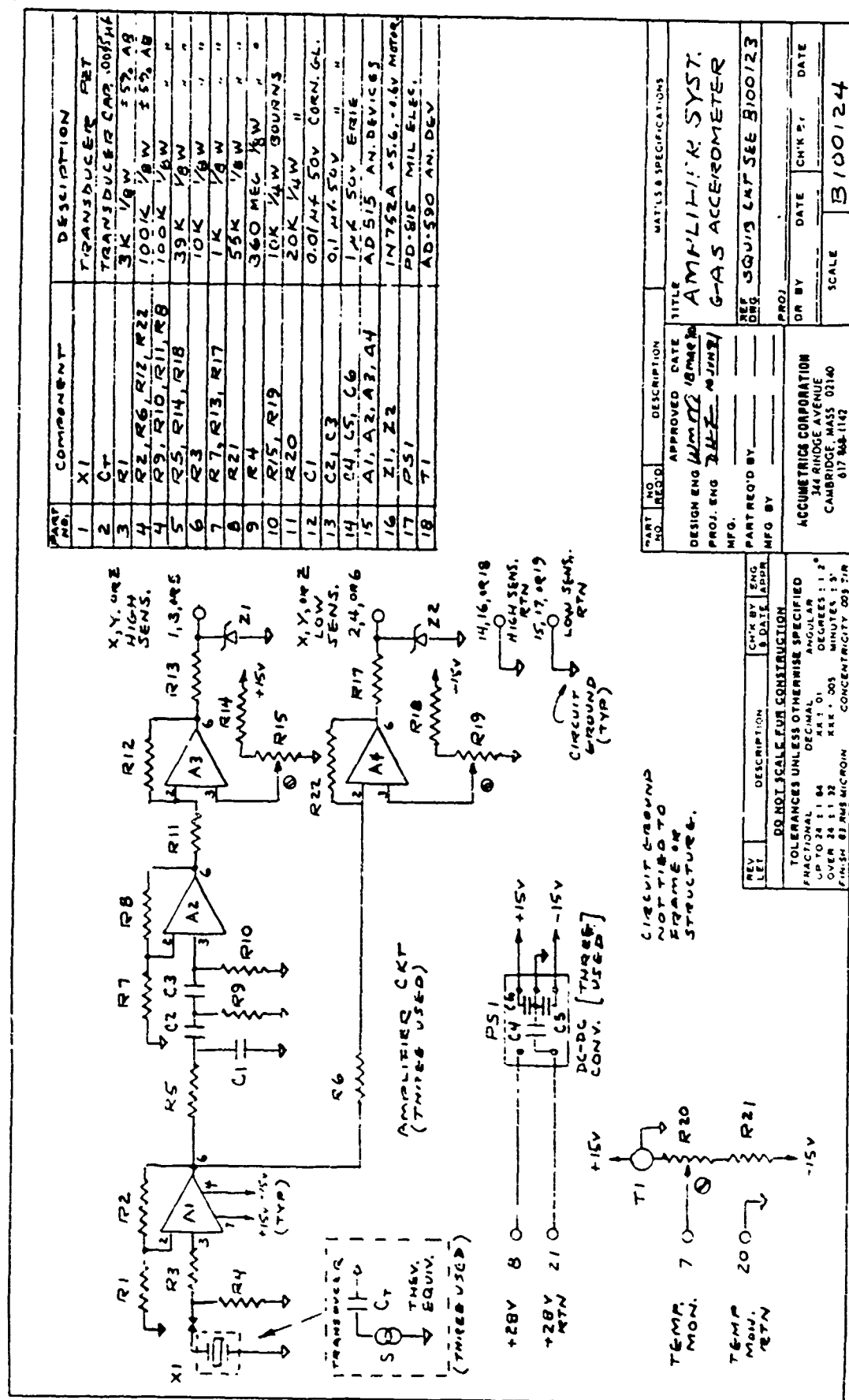
Three amplifier chains are used in the accelerometer, one for each coordinate axis. These amplifiers condition the transducer signals to provide the necessary amplitude, data zero offset, and band-edge limiting required by the interfacing TM/tape recorder system.

The total dynamic output of the transducer is placed in two channels each covering two decades of range. This is accomplished by providing two outputs for each amplifier chain.

The amplifier chains are fed by separate DC-DC converters and are separately shielded to avoid common impedance and electrostatic coupling between coordinate channels to avoid cross-talk interference. Two grounds are maintained throughout: structure ground and a circuit ground. No signal returns are carried through the structure. The signal ground is not connected to the structure of the accelerometer as it is intended that this ground be tied to the single point structure ground established by the user.

5.2 Design

Referring to Figure 7, operational amplifiers A1 and A2 are cascaded amplifiers providing the necessary signal amplification. In addition, A1 presents the



required low noise/high impedance termination for the transducer. The RC coupling network between these amplifiers provides roll-off at each end of the band-pass spectrum to reduce the amplifier noise.

Amplifiers A3 and A4 are connected as zero gain offset circuits to place the data zeroes at +2.5 volts. A3 conditions the high sensitivity data while A4 conditions a signal tapped off the output of A1 to provide the low sensitivity data. Zener diodes Z1 and Z2 limit the output swings to +5.6 volts and -0.6 volts.

6. SQUIB DRIVER CIRCUIT

6.1 General

A squib driver system is provided as a separate circuit potted within the electronics module of the GAS accelerometer. This circuit provides current pulses of sufficient amplitude and duration to initiate the six dimple motor squibs which generate the forces required to uncage the accelerometer after orbit is achieved.

The circuit is basically a capacitor-dump type where capacitors are trickle-charged from a +28 VDC source through resistors, and where relays are used to place the charged capacitors across the squibs when initiation is desired.

6.2 Design

Referring to Figure 8, the three RC circuits comprised of R1, R2, R3, C1, C2, and C3 are across the +28 VDC supply and hence the capacitors are charged. When relays RE1 and RE2 are energized, these capacitors are connected to the dimple motor squibs in a redundant manner. The capacitors discharge through the squibs at a current level permitted by the current regulators U1 through U6.

The current regulators are set to a level 25% greater than the all-fire current required by the DM25 J5 squibs. The RC energy storage circuits are sized so that the pulse duration will be five times the

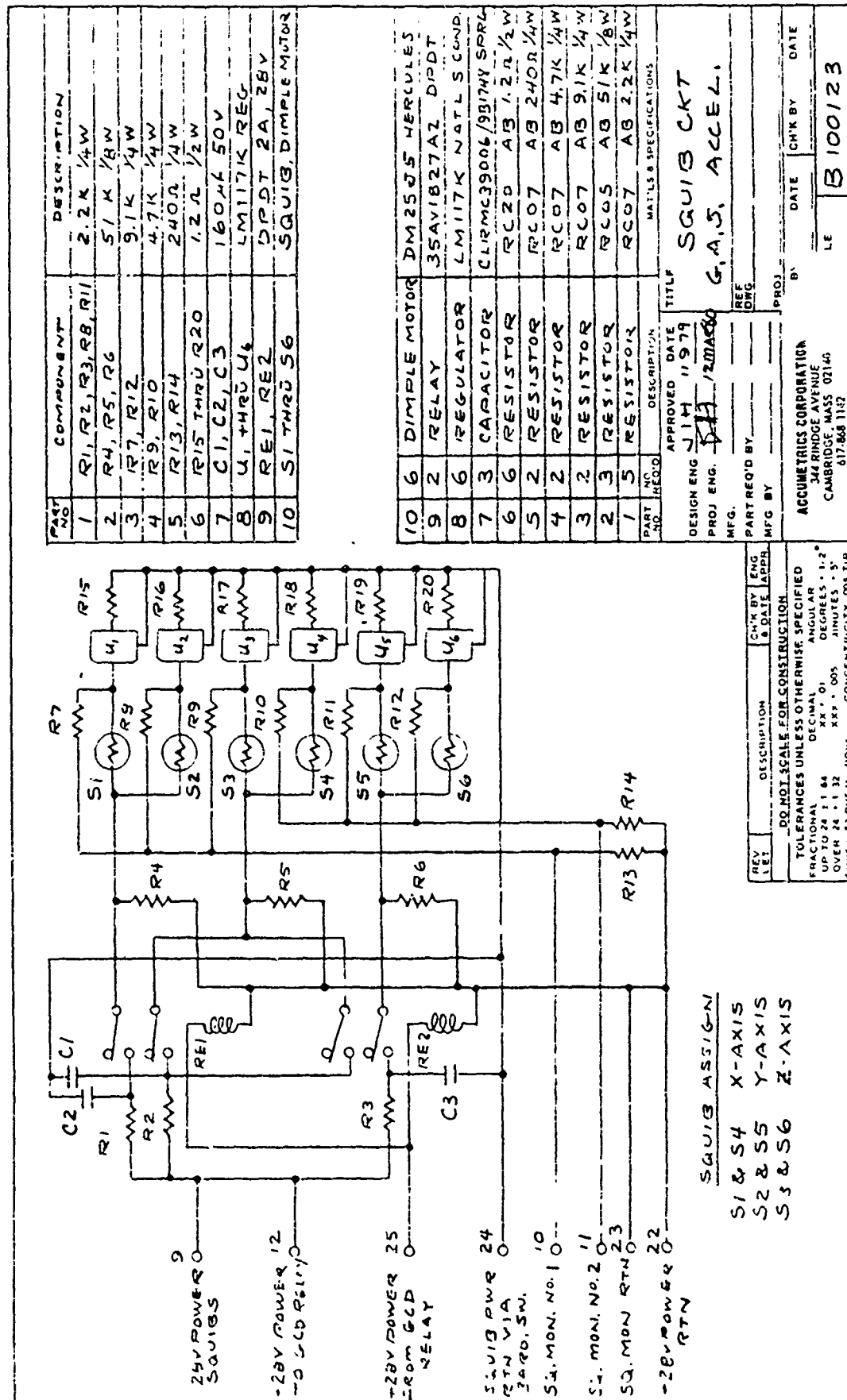


FIGURE 8

required ignition time.

The current pulse is essentially a trapezoidal pulse having an amplitude of 1.25 amperes holding for a duration of 1.3 milliseconds, then trailing off to zero in an additional 1.7 milliseconds.

As seen in the figure, monitors are provided to ascertain the condition of the squib bridge wires. Additionally, the energy storage RC circuits are interlocked by a baro-switch (in the GAS capsule) to prevent inadvertent sea-level squib initiation.

7. TEMPERATURE MONITOR

7.1 General

Provision has been made to monitor the accelerometer temperature during operation. This system incorporates a transducer which is potted into the electronics module. Since the electronics module is in contact with the accelerometer modules and all are fabricated of heavy aluminum, the total package is essentially iso-thermal thus transducer temperatures represent package temperatures throughout the system to good accuracy.

7.2 Design

The sensor is a two-terminal integrated circuit device which produces an output current proportional to temperature. This device is connected into a simple circuit as shown in Figure 7. The calibration curve for the temperature monitor circuit is shown in Figure 9.

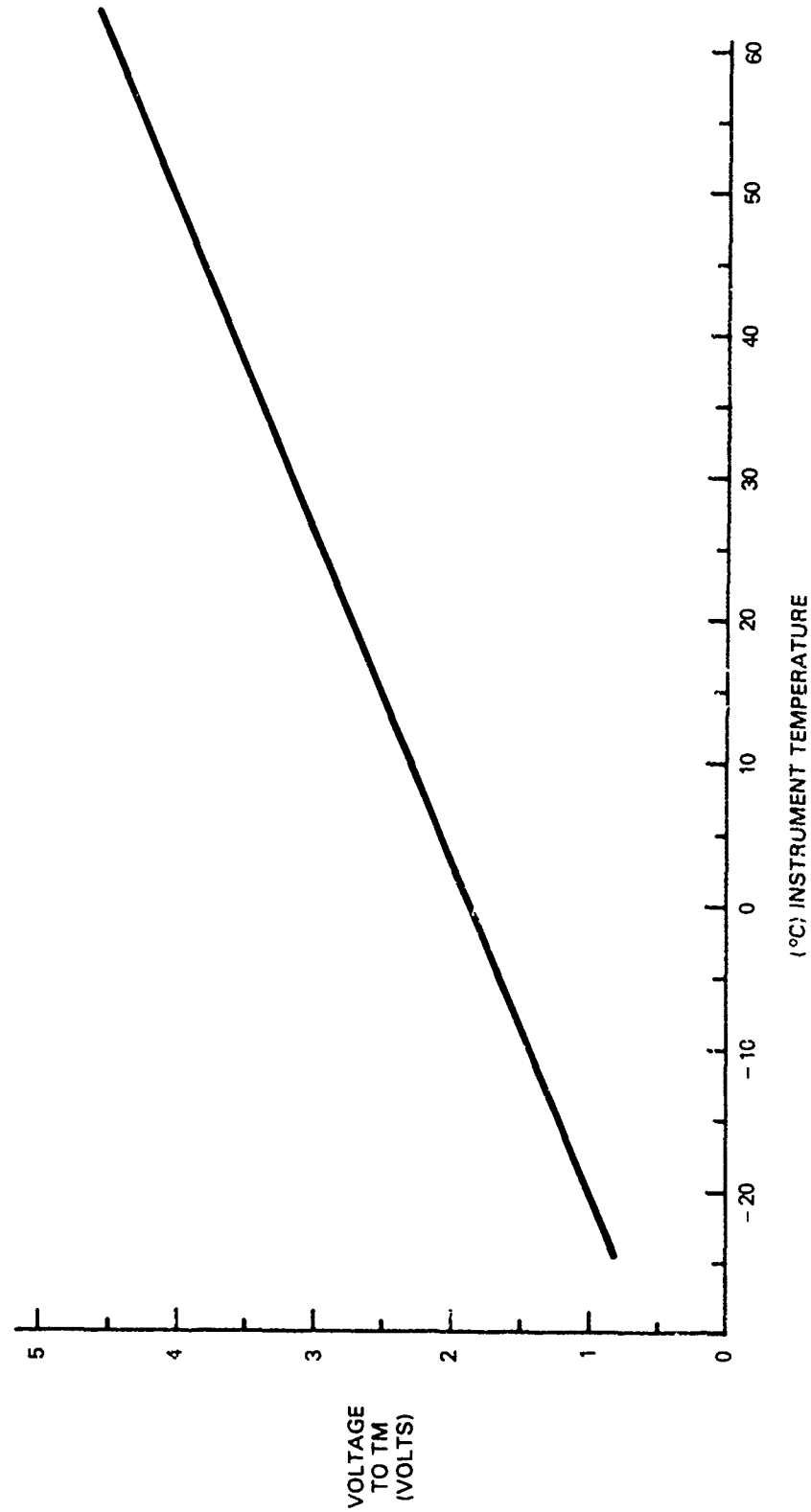


Figure 9

GAS MICRO-g ACCELEROMETER TEMPERATURE CALIBRATION

8. TESTING

8.1 General

Testing of the micro-g GAS accelerometer system, in addition to the usual performance testing required for development, consisted of operational temperature tests, vibration and shock exposure, and damping fluid seal integrity tests.

8.2 Temperature Tests

The components of the accelerometer system were tested separately at temperatures of -20°C , room, and 65°C . A one-hour soak was used at each temperature level. Performance for all tests was satisfactory.

8.3 Vibration and Shock

The components of the accelerometer system were tested along all three coordinate axes for random vibration integrity at a level of $0.15 \text{ g}^2/\text{Hz}$ over a 30 to 1000 Hz spectrum having a peak of $0.48 \text{ g}^2/\text{Hz}$ at 500 Hz for a duration of one minute per axis. Additionally, all three axes were exposed to 20g, 11ms half sinewave shock. No malfunction occurred during these tests.

8.4 Damping Fluid Seal Tests

The accelerometer modules were tested for seal integrity by first pressurizing the units with 20 psi air pressure for 24 hours, followed by a one-hour exposure in a vacuum chamber pumped down to 10^{-3} mm of Hg.

After preliminary tests revealed leaks, the units were redesigned to improve the seals, which after repeat testing, proved satisfactory.

9. CALIBRATION

9.1 General

Calibration of sensitive accelerometers is made difficult by the ambient seismic noise generated in the laboratory by highway traffic, wind (causing building movement and nearby tree root movement), and other earth tremors. Because the piezoelectric crystal is inherently linear in its stress-strain function when in a low-stress regime it is convenient to calibrate the transducer at accelerations above the ambient noise, and above its operating range, and by using its straight line characteristic to extrapolate down into the desired measuring range.

This linear characteristic was verified with PZT bimorph elements at Rockport, MA in 1971 where a very large granite ledge is available and where seismic noise, on calm days, is at 10^{-8} g. Measurements indicated that the transducer is linear down to the amplifier input noise level.

Using the above technique it is seen that the transducer and amplifier system must be calibrated separately because the amplifier would saturate at the calibration level of transducer output.

9.2 Amplifier Calibration

Amplifier calibration proceeded with the simulation of sensor voltages by means of a precision resistance

decade divider. Known voltages were produced by a signal generator which were divided to obtain values corresponding to expected sensor voltages. The internal capacitance of the bimorph element was simulated by the use of a fixed capacitance equal to that of the bimorph in series with the decade divider. Determination of frequency response, electrical noise level, and amplifier gain was accomplished with this test setup. Frequency and voltages were measured against standards traceable to the Bureau of Standards.

9.3 Transducer Calibration

Calibration of the transducer was accomplished by the use of a sine wave displacement generator and a microscope mounted onto the calibration system platform. Displacements were measured by observing the peak-to-peak excursion of a fine line scribed on the base of the transducer. This displacement is a measure of the input acceleration through the relationship

$$\chi = X \sin \omega t$$

which becomes

$$\ddot{\chi} = a = -X \omega^2 \sin \omega t$$

Thus the magnitude of peak-to-peak acceleration is

$$a = X \omega^2$$

where $\omega=2\pi f$ is the input frequency of the generator and X is the peak-to-peak displacement of the base of the transducer. The combined amplifier and transducer calibrations then provided the system calibration. The curves of Figure 10 is the result of this effort.

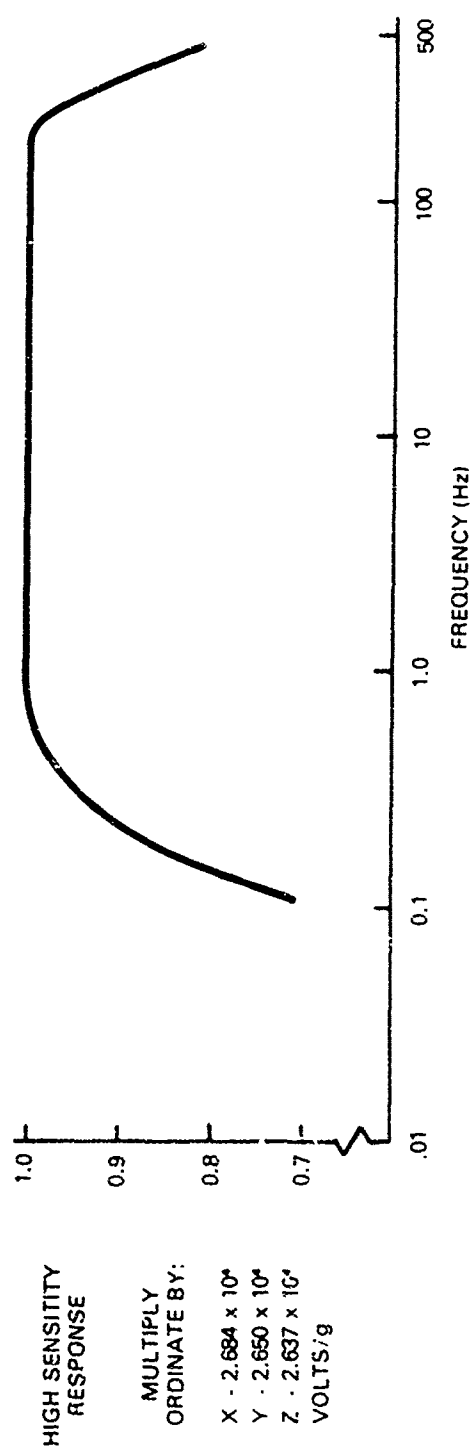
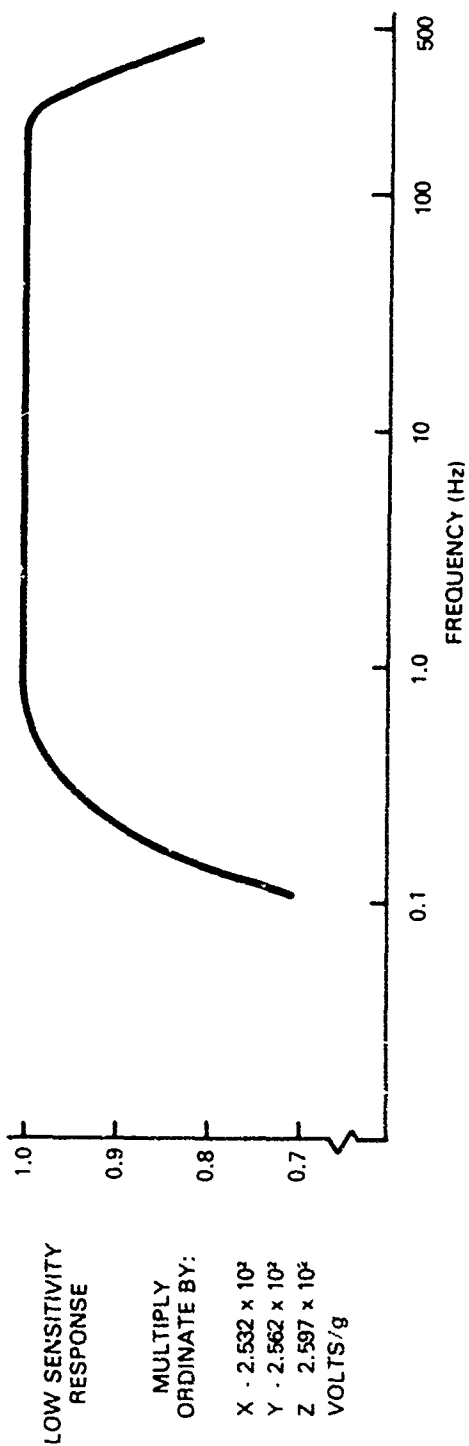


Figure 10
GAS MICRO-g ACCELEROMETER CALIBRATION